PHILOSOPHICAL SOCIETY OF WASHINGTON
BULLETIN VOL. XI, pp. 191-220.

THE

MINERAL COMPOSITION AND GEOLOGICAL OCCURRENCE

OF CERTAIN

IGNEOUS ROCKS

IN THE

YELLOWSTONE NATIONAL PARK.

BY

JOSEPH PAXSON IDDINGS.

READ BEFORE THE PHILOSOPHICAL SOCIETY OF WASHINGTON,
JANUARY 18, 1890.

WASHINGTON:
PUBLISHED BY THE SOCIETY
FEBRUARY, 1890.

UI B

THE MINERAL COMPOSITION AND GEOLOGICAL OCCURRENCE OF CERTAIN IGNEOUS ROCKS IN THE YELLOWSTONE NATIONAL PARK.

BY

JOSEPH PAXSON IDDINGS.

[Read before the Society by permission of the Director of the U. S. Geological Survey, January 18, 1890.]

INTRODUCTION.

That there is a connection between the *geological occurrence* of igneous rocks and their *crystalline structure* is very generally admitted; when by the geological occurrence is meant the mode of occurrence of such rocks as dikes, stocks or necks, laccolites, or irregularly shaped masses of variable dimensions enclosed within other bodies of rock, or as extravasated masses which assume the form of lava-flows, breccias, pumices, and tuffs.

But the term should be extended so as to include the *geological history* of the eruption. For the nature of this relation is not definite or fixed, since the crystalline structure of different rock-masses not only varies with the size and character of the geological bodies in which they occur, but more especially with certain conditions attending the solidification of the magmas, including those connected with the whole history of their eruption.

The extent of these variations in structure is becoming better understood as the geological investigation of igneous

rocks in the field and their petrographical examination advance hand in hand.

The relation, however, between the *geological occurrence* and the *mineral composition* of igneous rocks is less understood, and seems not to have entered sufficiently into the consideration of these rocks as crystallized magmas. This relation is a matter of fundamental importance for the establishment of the proper connection between different varieties of eruptive rocks, which necessarily underlies a natural system of their classification.

The study of the igneous rocks at Electric Peak and Sepulchre Mountain—incidental to the investigation of the Yellowstone National Park under the charge of Mr. Arnold Hague—offers a valuable contribution to our knowledge of these relations. In order to present some of the results of this study it will be necessary to sketch the geology of the region and describe the eruptive rocks occurring in it. After which the variations in their mineral composition and crystalline structure will be discussed.

Geological Sketch of the Region.

Electric Peak is the highest point of that portion of the Gallatin Mountains lying within the Yellowstone National Park, and reaches an altitude of 11,100 feet. It has been carved out of Cretaceous shales and sandstones, which, with the underlying strata of this range of mountains dip gradually toward the northeast. Occupying a synclinal trough between two bodies of Archæan gneiss, these strata have undergone more or less folding and displacement, which has been accompanied by the eruption of igneous magmas.

The earlier of these eruptions forced sheets and laccolites of intrusive rocks between the strata wherever the nature of the beds offered planes of least resistance to the dynamical forces engaged in their plication. Hence the sheets are more abundant and smaller where the strata were very fissile, and abound in the shales and thinly bedded sandstones of the Cretaceous. The mass of Electric Peak is

traversed by sheets of porphyrite, which have been intruded from a centre of eruption southwest of the mountain.

A subsequent synclinal break along what is now the east side of the mountain, permitted the further eruption of igneous material, which penetrated the nearly vertical fissures caused by this fracture. These vertical dikes traverse the strata and intercalated sheets in the main body of the mountain, but are nearly parallel to them in that portion of the mass east of the synclinal axis where the beds have been turned up on end. The dikes radiate from about the middle of the northeast spur of the mountain through an arc of 45° from south to southwest, and are not more than a mile and a half long. At the centre from which they radiate is a broad stock of intrusive rocks 1,500 feet wide, which lies in the axis of the synclinal. From it branch several apophyses, and around it the sedimentary rocks have been highly metamorphosed.

The eruptive magmas which found their way between the ruptured strata and solidified as intrusive rocks in the form of laccolites, sheets, dikes and stocks, also reached the surface of the earth in places and cooled as effusive bodies. The extravasated rocks were probably erupted from a number of different vents, whose position was governed by the nature and extent of the fissures in the sedimentary rocks. They poured out as flows of lava and were from time to time blown to pieces and thrown into great accumulations of breccia. These in turn were intersected by dikes and stocks of subsequently erupted magmas, that solidified as intrusive bodies within the effusive rocks.

This is the condition of things at Sepulchre Mountain, which is directly east of Electric Peak across the valley of Reese Creek. The mass of this mountain is made up of volcanic breccias and lava-flows and tuffs, which rest upon Cretaceous strata and exhibit little or no evidence of bedding. The western portion of the mass at the base of the mountain is filled with dikes and larger intruded bodies of igneous rocks, which also form the low ridges and hills between

these two mountains. The dikes are later eruptions through the breccia, and trend from the vicinity of Cache Pond in a north and northeast direction, some trending east. In a general way they radiate in the opposite direction to those in Electric Peak.

The mass of Sepulchre Mountain with the body of intrusive rocks at its west base is separated from Electric Peak by a profound fault that trends north and south, and has thrown the higher surface accumulations of Sepulchre Mountain below the level of the Cretaceous strata with their deep-seated bodies of intruded rocks.

The eruptive rocks at the western edge of the Sepulchre Mountain mass, and directly east of the plane of faulting, carry large blocks of black Cretaceous shale, showing that they have broken up through the same strata as those forming Electric Peak. The effect of the faulting on the eruptive rocks along the east side of the fault is plainly seen. The rocks are shattered and fractured into small pieces, held together by the pulverized portion.

Petrographical Notice of the Various Rocks.

An investigation of all of the igneous rocks embraced within this small area reveals a great number of important and interesting facts, which it would be impossible to present at one time to the attention of the society. In the present paper it will be sufficient to notice some of the more general observations before describing those more intimately connected with the subject in hand.

Electric Peak.—The rock-bodies forming the sheets that were intruded into the mass of Electric Peak before the intrusion of the dikes consist of a group of fine grained porphyrites. They are holocrystalline with slight variations in the grain of the groundmass. They form a group of rocks varying in chemical and mineralogical characters within certain limits. Thus they may be arranged under five different divisions, which grade into one another mineralogically, and may be tabulated with reference to the phenocrysts

other than plagioclase, which is common to all the varieties, as in the following table:

TABLE I.

Variation of Phenocrysts in the sheet-rocks at Electric Peak.

(*a*)	**pyroxene**			
(*b*)		**hornblende**		
(*c*)		**hornblende**	biotite	
(*d*)		HORNBLENDE	BIOTITE	
(*e*)		hornblende	**biotite**	quartz

The variations in the mineral composition are accompanied by changes in the character and amount of the feldspars. Toward the end of the series in the order given the feldspars become less basic and more abundant and are associated with an increasing amount of quartz in the groundmass of the rock. The proportion of ferromagnesian silicates decreases from the pyroxene end toward the mica end of the series.

The intrusion of these sheet-rocks was not the result of a single eruptive action, but of a succession of eruptions; hence we observe that there was a period of volcanic activity that injected into the mass of Electric Peak a series of magmas which solidified as pyroxene-porphyrite, hornblende-porphyrite, and hornblende-biotite-porphyrite.

Subsequently another period of activity filled the eastern portion of the mountain with dikes and the stock. The magmas forced up at this period solidified as porphyrites and diorites, which grade into one another structurally and mineralogically. The coarse grained rocks, the diorites, occur in the stock and larger apophyses; the porphyrites occupy the dikes and smaller apophyses, and are found along the sides of the stock in places, in contact with the sedimentary rocks.

The great body of diorite varies both in structure and composition; the variations being rapid in some places, and very irregular. It is mostly a dark-colored granular rock,

eomposed of ferromagnesian silicates and feldspar; parts of it are light-eolored with a noticeable pereentage of quartz. It is traversed by veins or dikes of light-eolored diorites, and shows by breeciated portions that the whole mass is made up of a number of bodies that have followed one another up through the main fissure at short intervals of time.

The minerals eomposing the diorites are: hypersthene, augite, hornblende, biotite, lime-soda-feldspar (labradorite), orthoelase and quartz. The relative proportions of these vary eonsiderably as already noted. The erystallization of the eoarser grained diorites appears to have been a eontinuous, uninterrupted act; all of the minerals ineluding the aecessory ones having eome within the influenee of the eauses producing the granular strueture. In the finer grained, porphyritie portions of the diorite mass it is evident that the initial tendeney of erystallization led to the formation of hypersthene and augite, and also hornblende in some eases, and that the biotite was a later erystallization conneeted with the final eonsolidation of the roek. In the non-porphyritie, granular forms of the diorite, it is also evident that the earlier erystallizations were of hypersthene and augite and of part of the hornblende, while the greater part of the hornblende, and the biotite followed. The labradorite eommenced to crystallize early, while the alkali plagioelase, orthoelase and quartz elosed the series.

The last eruption through this ehannel was that of a quite silieeous magma, solidifying as quartz-biotite-diorite-porphyrite, whieh approaches granite-porphyry in composition. It is a light-colored, fine grained roek with abundant phenocrysts of plagioelase, biotite and quartz, with a little hornblende in plaees. It forms a broad body within the diorite, with a few dikes of still finer grained roek traversing the strata to the southwest.

The mineral variation in the roeks within the stock is shown in the aeeompaning table in which (*a*) (*b*), ete., represent different modifieations of the rock.

Table II.

Mineral variation of the diorites and their facies at Electric Peak.

(*a*)	pyroxene		biotite	labradorite	OLIGOCLASE		quartz
(*b*)	pyroxene	hornblende	BIOTITE	labradorite	OLIGOCLASE		quartz
(*c*)	pyroxene	hornblende	biotite	LABRADORITE	OLIGOCLASE	orthoclase	QUARTZ
(*d*)		hornblende	biotite	LABRADORITE	OLIGOCLASE	orthoclase	quartz
(*e*)		HORNBLENDE	biotite	labradorite	oligoclase	orthoclase	quartz
(*f*)		hornblende	biotite		oligoclase	orthoclase	quartz
(*g*)			biotite		oligoclase	ORTHOCLASE	quartz

The porphyrites associated with the diorites vary in mineral composition from those with phenocrysts of pyroxene and some hornblende, through varieties with hornblende and biotite, to those with biotite and quartz, plagioclase being common to them all. The series is represented by the following table:

Table III.

Variation of phenocrysts in the porphyrites at Electric Peak.

(*a*)	pyroxene			
(*b*)	pyroxene	hornblende		
(*c*)	PYROXENE	HORNBLENDE		
(*d*)	pyroxene	hornblende		
(*e*)		hornblende		
(*f*)		hornblende	biotite	
(*g*)		hornblende	BIOTITE	
(*h*)		hornblende	biotite	
(*i*)		hornblende	biotite	
(*j*)			BIOTITE	quartz

The variation in the nature and abundance of the porphyritical ferromagnesian silicates is accompanied by a gradual change in the character of the plagioclase, which is more basic at the pyroxene end of the series; besides a

change in the character of the groundmass, which is richer in quartz and assumes a more granular structure toward the mica end of the series.

The course of volcanic events at Electric Peak, then, commenced with successive intrusions between the sedimentary strata of a series of porphyrites. A later series of magmas came up through vertical fissures and a central conduit. These later magmas imparted a great amount of heat to the rocks immediately surrounding the conduit, and highly metamorphosed them. The magmas which followed one another through the conduit broke through those that had previously solidified within it, but had not entirely cooled. They solidified in the outlying, narrow fissures as dikes of porphyrite, while within the heated conduit they consolidated into coarse grained diorites of various kinds; the magmas of this series of eruptions becoming more and more siliceous.

The succession of eruptions may be expressed as in the first half of the table on the opposite page.

Sepulchre Mountain.—The eruptive rocks lying east of the fault line embrace a large body of extravasated breccias with smaller bodies of dikes that have broken through the breccia. The whole group of rocks coming within the generally accepted class of volcanic rocks.

The breccias which form the main mass of Sepulchre Mountain and extend as far west as the fault consist of fragments of various kinds of andesites. The lowest portion is made up of acidic andesites, that are characterized by phenocrysts of biotite, hornblende and plagioclase. They are light-colored rocks, passing in places into fine tuffs. This, the oldest breccia, carries a great amount of Archæan material in fragments, which are not found in the later, overlying breccias. Over the acidic breccia is a dark-colored one of basic andesite with inconspicuous phenocrysts of pyroxene and plagioclase, and a variable amount of hornblende. Higher up the breccia becomes grayer, and carries more hornblende phenocrysts. Some of the dark-colored

TABLE IV.

Succession of Eruptions at Electric Peak.	Succession of Eruptions at Sepulchre Mountain.
A. Intrusion of sheets of **porphyrite** from the southwest.	A. Extravasation of **andesitic breccia** from some Archæan area.
B. Intrusion of **dike- and stock-rocks** in the following order:	B. Eruption of **andesitic breccias and dikes** in the following order:
pyroxene-porphyrites, grading into	**pyroxene-andesites,** breccia and flows passing into
pyroxene- and hornblende-diorites with biotite of final crystallization, with dikes of pyroxene- and hornblende-porphyrites, grading into	**pyroxene-hornblende-andesites,** breccia and flows with dikes of similar andesites, grading into
hornblende-biotite-diorites with biotite of early crystallization, with dikes of hornblende-biotite-porphyrites;	**hornblende-biotite-andesites** in dikes, grading into
quartz-biotite-diorite-porphyrite with some hornblende, with dikes of quartz-biotite-porphyrite.	**dacites** with phenocrysts of quartz, biotite and some hornblende.

breccia is quite basaltic looking, while the grayer breccia has an andesitic habit. They are very intimately associated, however, with no line of demarcation between them. The upper breccias are distinguished from the lowest by the presence of pyroxene and the absence of biotite. The bottom breccia is made up of hornblende-mica-andesites, the upper breccias of pyroxene-andesites and hornblende-pyroxene-andesites.

The breccias and flows of massive lava occurring in the upper portion of the mountain, differ among themselves in color and macroscopical habit, that is, in the abundance and proportion of groundmass and phenocrysts. They also differ in the relative abundance of the various essential minerals, and in the chemical composition of the rocks within certain limits.

They have all the petrographical characteristics of volcanic lavas; they are mostly glassy, with a porous or vesicular texture; some are compact, and some, holocrystalline.

The dikes that have broken through these breccias and are consequently of younger age, have furnished a series of rocks that vary among themselves mineralogically and chemically. The earliest of these dikes consist of hornblende-andesite with large hornblende phenocrysts; a few are pyroxene-andesite. They are so closely allied petrographically to the flow-rocks of the uppermost breccia that it is probable that they may be the same magmas which solidified as dikes during the extravasation of the hornblende-pyroxene-andesitic breccias and flows.

Later dikes consist of hornblende-mica-andesite, with abundant small phenocrysts of hornblende, biotite and plagioclase. Between these two varieties of andesite are all possible gradations, caused by the variations in the amount of biotite, and in the general habit of the rocks.

These rocks in turn grade into still more micaceous varieties which carry phenocrysts of quartz, and as the extreme variety present a quartz-mica-plagioclase rock with little hornblende. These dacites were the last to break up, and the

most acid variety appears to have closed the series of eruptions that built up Sepulchre Mountain.

It is evident from a study of these dikes in the field that they were formed by a succession of eruptive actions, which fissured the breccias and filled the cracks with magmas that differed chemically and mineralogically; and that, starting with magmas resembling those of the latest breccias, they became more and more siliceous.

The andesitic breccias and dikes form a continuous petrographical series, which may be divided for convenience into varieties that differ in the nature of the porphyritical minerals as represented in the accompanying table, plagioclase being present in all.

TABLE V.

Variation of phenocrysts in the rocks of Sepulchre Mountain.

(*a*)	PYROXENE			
(*b*)	pyroxene	hornblende		
(*c*)		HORNBLENDE		
(*d*)		HORNBLENDE	biotite	
(*e*)		hornblende	biotite	quartz
(*f*)			BIOTITE	QUARTZ

The dike rocks are porous and vesicular in the smaller dikes and are sometimes glassy. In the larger bodies they are more compact and usually quite crystalline.

The course of events at Sepulchre Mountain may be expressed as follows, and as tabulated on the second half of Table IV, page 199: An acidic, andesitic breccia carrying a great amount of Archæan fragments was spread upon the surface of the country. It rests upon Cretaceous strata, and was probably thrown from some neighboring area of Archæan schists and gneisses. Such an area at present exists to the north, across the Yellowstone river.

Upon this were thrown breccias with massive flows of

pyroxene-andesite, followed by those of hornblende-pyroxene-andesite. These were intersected by dikes of the same andesites, followed by hornblende-mica-andesites and dacites, which closed the series. The upper portion of this volcano having been removed, the surface-flows of the later magmas are not known in this region.

Comparison of the Rocks at Electric Peak with those at Sepulchre Mountain.

Upon comparing the Tables (No. IV) representing the succession of eruptions at Electric Peak and at Sepulchre Mountain, the correspondence between the two is at once striking, but not more so than the correspondence between the rocks themselves. Leaving out of consideration the eruptions embraced in the divisions A, which evidently emanated from different sources; we observe that the series of magmas that were erupted successively, and solidified within the strata of Electric Peak as porphyrites and diorites, and those that consolidated into the mass of Sepulchre Mountain are similar; that each series commenced with basic magmas and closed with acidic ones. Their division in the table into four groups is not intended to convey the idea that they belong to four distinct periods of eruption. The whole series in each case is more correctly a single, irregularly interrupted succession of outbursts of magma that gradually changed its composition and character.

When we compare the rocks that have resulted from the corresponding phases of these series of eruptions, the similarity of the porphyritic forms is immediately recognized. The nature and distribution of the phenocrysts in the different varieties of andesite and dacite, which determine their macroscopical habit, have their exact counterparts in the different varities of porphyrites. The microscopical characters of the phenocrysts in the corresponding varieties of porphyrites and of the intruded andesites and dacites are identical. The character of the various groundmasses, however, is differ-

ent in the two groups, being more highly crystalline in the porphyrites—many of the andesites being glassy. Many of the finer grained diorites have a habit, derived from the distribution of the ferromagnesian silicates and larger feldspars, which resembles that of some of the andesites and dacites which correspond to them chemically. But the coarse grained diorites bear no resemblence to the andesites in outward appearance or in mineral composition.

Chemical Characters of the Rocks.

The chemical investigation of these rocks not only brings out more clearly the similarity between the two groups of rocks under consideration, but establishes their chemical identity, and permits of the comparison of those modifications of the magmas which bear no mineralogical or structural resemblance to one another.

The analyses of the rocks occuring at Electric Peak, together with analyses of two of the sheet-rocks, are given in Table VI, p. 206. They were made by Mr. J. E. Whitfield. With the exception of the two analyses of sheet-rocks, which are introduced for comparison, they have all been made from rocks occurring within the area of the main stock in Electric Peak, and represent the composition of various forms of the diorite and the diorite-porphyrite. The first three analyses are from the main body of coarse grained diorite, and show its variation between 56 and 58 per cent. of silica, with irregular variations in the other chemical constituents, especially in the alumina and magnesia. The next two analyses are from porphyrites occurring in sheets, which resemble certain of the porphyrites occurring in dikes and have been introduced in the table to show their similarity, and to fill up a gap between Nos. 2692 and 3008; it not being advisable to multiply too largely the chemical work on this particular group of rocks since others of equal importance command their share of attention.

That this insertion is admissible is shown by the accompanying list of silica percentages, determined for different modifications and varieties of this group of rocks.

TABLE VII.

Silica Percentages of the Rocks from Electric Peak.

53.72	58.10	61.50	65.80
55.23	58.11	61.85	65.94
55.64	58.49	63.01	65.97
56.28	58.87	63.78	66.05
56.33	59.64	64.85	67.54
57.12	60.54	65.11	69.24
57.38	60.56	65.48	
58.05	60.89	65.60	

They were intended to supplement the complete analyses in order to demonstrate what is evident from the microscopical study of the thin sections, namely: that the different varieties of porphyrites and diorites pass through all possible gradations from one extreme to the other. The character of this transition is shown by the accompanying diagram, in which each determination is given the same weight, the series being arranged according to the increase of silica, and the silica percentages plotted as ordinates.

The next three analyses of Table VI, Nos. 3008, 2724, 2695, are from the main body of the diorite, No. 3008 being a light colored vein or dike of diorite in the darker mass. Nos. 2668 and 2676 are diorites from the main stock; and Nos. 3001 and 2670 are from the quartz-mica-diorite-porphyrite, occurring within the main stock. These latter analyses vary from 64.85 to 69.24 per cent. of silica.

The variations of the other chemical constituents are best

comprehended by comparing their molecular proportions. This has been done graphically as in the accompanying diagram Table VIII, in which the molecular proportions of the principal oxides are plotted as ordinates, those of the silica being taken as abscissas. The point of origin of the latter is some distance to the left of the diagram.

The first impression derived from the diagram is that of the irregularity of the variations in all of the oxides besides silica, magnesia being the most erratic. The second impression is that of the apparent independence of the variations of the different oxide molecules. But this independence disappears upon closer study and certain evidences of sympathy become very marked. The most striking evidence of this exists between the ferrous and ferric oxides; they are noticeably inversely proportional to one another, an increase of ferrous oxide being accompanied by a decrease of ferric oxide. The total amount of iron varies irregularly, decreasing from the basic to the acidic end of the series. Each of the iron oxides seems to be quite independent of the magnesia. The most regular variation is that of the lime, which decreases steadily from the basic to the acidic end of the series. The magnesia drops very rapidly at first, and is very irregular in the more siliceous end of the series. The alumina, though quite irregular between certain limits, maintains a uniformly high position, being largely in excess of any one of the other oxides, except silica. The alkalies are most like the alumina in their variations and remain very nearly uniform, increasing slightly toward the siliceous end of the series. The soda molecules are more than twice as numerous as those of the potash. In the basic end of the series the alkalies vary together in the same direction, while in the more siliceous end they vary in opposite directions.

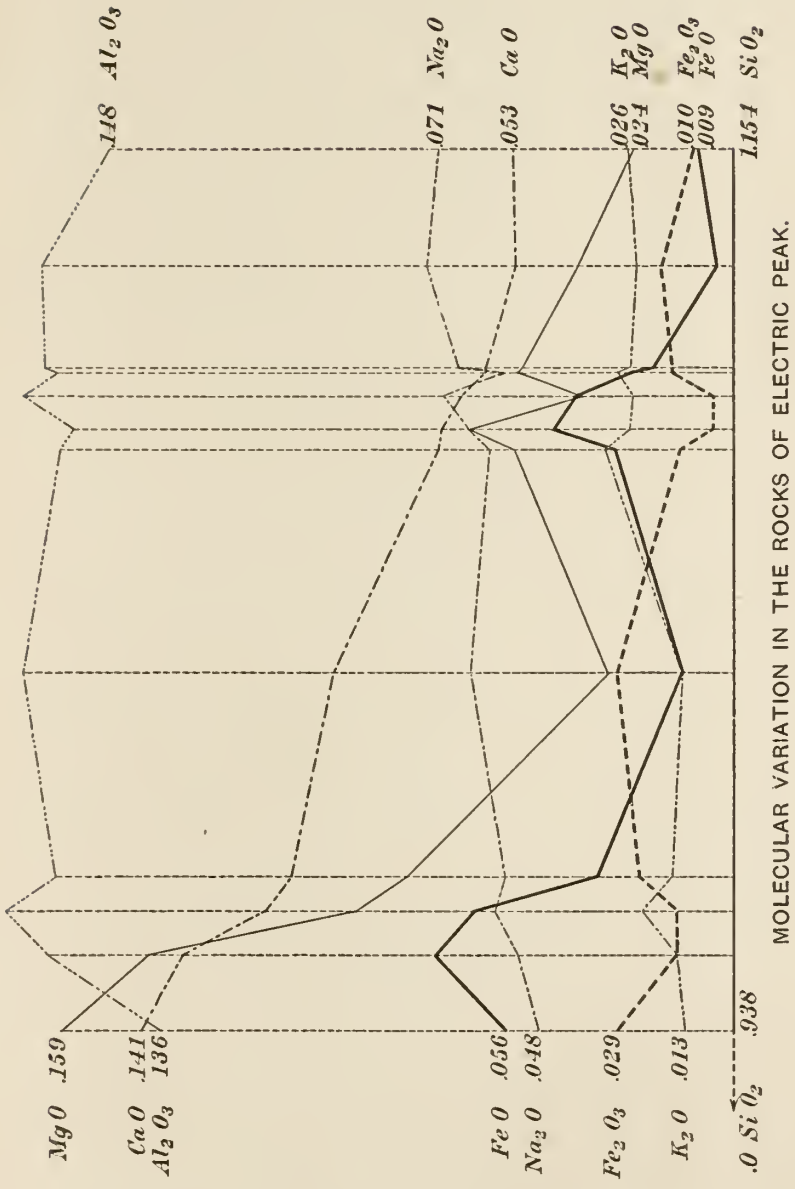
There is a marked accordance between the soda and alumina, both varying in the same direction, with one exception, though not to the same extent. There is an equally marked discordance between the alumina and magnesia, which, with one exception, vary in opposite directions.

TABLE VI.

Chemical analyses of intrusive rocks from Electric Peak.

Specimen number.	2669	2679	2692	2089	154	3008	2724	2695	3001	2668	2676	2670
SiO_2 . . .	56.28	57.38	58.05	58.49	61.50	64.85	65.11	65.60	65.97	66.05	67.54	69.24
TiO_2 . . .	.84	tr.	1.05	1.71	none	.91	.71	.75	.42	.34	.80	.65
Al_2O_3 . . .	14.23	16.86	18.00	16.70	17.42	16.57	16.21	17.61	16.53	16.96	17.02	15.30
Fe_2O_3 . . .	4.69	2.49	2.49	3.85	4.66	2.10	1.06	.95	2.59	2.59	2.97	1.72
FeO	4.05	5.17	4.56	2.37	1.09	2.15	3.19	2.76	1.72	1.38	.34	.69
MnO . . .	.16	tr.	none	.24	tr.	none	none	none	none	none	tr.	tr.
CaO . . .	7.94	7.32	6.17	5.90	5.33	4.01	3.97	3.72	3.37	3.37	2.94	2.98
MgO . . .	6.37	5.51	3.55	3.12	1.26	2.14	2.57	1.49	2.11	2.08	1.51	.95
Li_2O . . .	.01	.39	none	.01	.03	none	.04	.03	.09	none	.03	none
Na_2O . . .	2.98	3.33	3.64	3.47	3.99	3.71	4.00	4.36	3.41	4.20	4.62	4.46
K_2O	1.23	1.45	2.18	1.59	1.29	3.10	2.51	2.36	2.67	2.53	2.28	2.52
P_2O_5	.40	tr.	.17	tr.	.60	.14	.02	.16	tr.	tr.	tr.	tr.
SO_3	tr.	.21	.07	.63	.35	tr.	tr.	tr.	.13	.03	.26	.27
Cl	.17	.17	tr.	. . .	. . .	none	none	none	.09	tr.	.15	tr.
H_2O	.93	.42	.86	2.44	2.44	.35	.94	.59	1.23	.69	.55	1.30
	100.28	100.70	100.79	100.52	99.96	100.03	100.33	100.38	100.33	100.22	101.01	100.08
Less O for Cl	.04	.04	. . .	. . .	. . .	. . .	. . .	. . .	.02	. . .	.03	
	100.24	100.66							100.31		100.98	

TABLE VIII.


MOLECULAR VARIATION IN THE ROCKS OF ELECTRIC PEAK.
Al2 O3
Na2 O
Ca O
K2 O
Mg O
Fe2 O3
Fe O
Si O2
148
071
053
026
024
010
009
1154
159
141
136
056
048
029
013
938
Mg O
Ca O
Al2 O3
Fe O
Na2 O
Fe2 O3
K2 O
Si O2
.0

It is to be remembered that these irregular variations take place not only between allied varieties of rocks, but in different parts of the same rock-body, and that they correspond to variations in the relative proportions of the essential minerals. When it is remembered that the essential minerals concerned in this group of rocks are: feldspars, pyroxenes, amphiboles, mica, quartz and magnetite, one or more of which may be absent from a particular form of the rock; and when we consider the number of different complex molecules into which any one of these oxide molecules enters, we begin to realize the interdependence of the variations among the oxide molecules. Thus while most of the alumina enters into the composition of the feldspar, a portion of it enters into the ferromagnesian silicates. The alkalies are mostly found in the feldspars, but the soda takes part in the augites and hornblendes, and the potash in the biotite. The lime is an important factor in both the feldspars and ferromagnesian silicates; it is most abundant in the basic plagioclases, and diminishes as the feldspars become more alkaline; it abounds in augite and to a less extent in hornblende, and is almost absent from hypersthene and biotite. The iron and magnesian molecules, however, have no part in the composition of the feldspars, and are confined to the ferromagnesian minerals.

Corresponding to the extremes of the series of chemical constituents are the simple minerals, magnetite and quartz, consisting of an uncombined oxide or oxides, which act as compensators to regulate the exhaustion of the oxide molecules in the magma; the magnetite expressing the iron oxide in excess of that entering into the complex silicate molecules; the quartz representing the excess of silica molecules.

From these considerations we begin to understand the relative variations expressed by the diagram. The inverse relation between the magnesia and alumina corresponds to variations in the complex molecules of feldspars and of the ferromagnesian silicates; an increase of feldspar molecules is accompanied by a decrease of ferromagnesian molecules.

The independently uniform variation in the lime molecules is consistent with the fact that it enters so largely into both the feldspar and the ferromagnesian molecules. Their steady diminution from the basic to the acidic end of the series is in accord with the decrease in the amount of augite and hornblende, and the increase of alkali feldspars, shown by the increase of soda and potash and silica.

The very noticeable reciprocal relation between the ferrous and ferric oxides indicates the variable oxidation of pre-existing molecules. And it is probable that the ferrous molecules were the original ones; moreover, when all of the iron is reduced to the form of ferrous oxide, its molecules are found to vary in the same direction, and almost to the same extent as those of magnesia. Since the hornblende and biotite are the ferromagnesian minerals, carrying the greatest percentage of ferric oxide, the variation in the oxidation of the iron is naturally in accord with the amount of these minerals in the rock. This is, however, significant from its bearing on the question of the development of hornblende and biotite in the coarser grained varieties of these rocks, and from its possible connection with the work of mineralizing agents.

The chemical composition of different varieties of the Sepulchre Mountain rocks is shown by the accompanying analyses, Table IX. Nos. 219, 694, 221, 2736 and 3680 were analyzed by Mr. J. E. Whitfield; Nos. 214, 217 and 394, by Dr. T. M. Chatard; and No. 3680 by Mr. L. G. Eakins.

The varieties represented are the two forms of breccia: pyroxene-andesite and hornblende-pyroxene-andesite. And the dike rocks including three varieties of andesite and dacite. They range from 55.83 to 67.49 per cent. of silica, very nearly the same as the group from Electric Peak.

The chemical variation of the group is expressed graphically by the diagram, Table X, showing the molecular proportions of the essential oxides, which have been plotted in the same manner as in Table VIII.

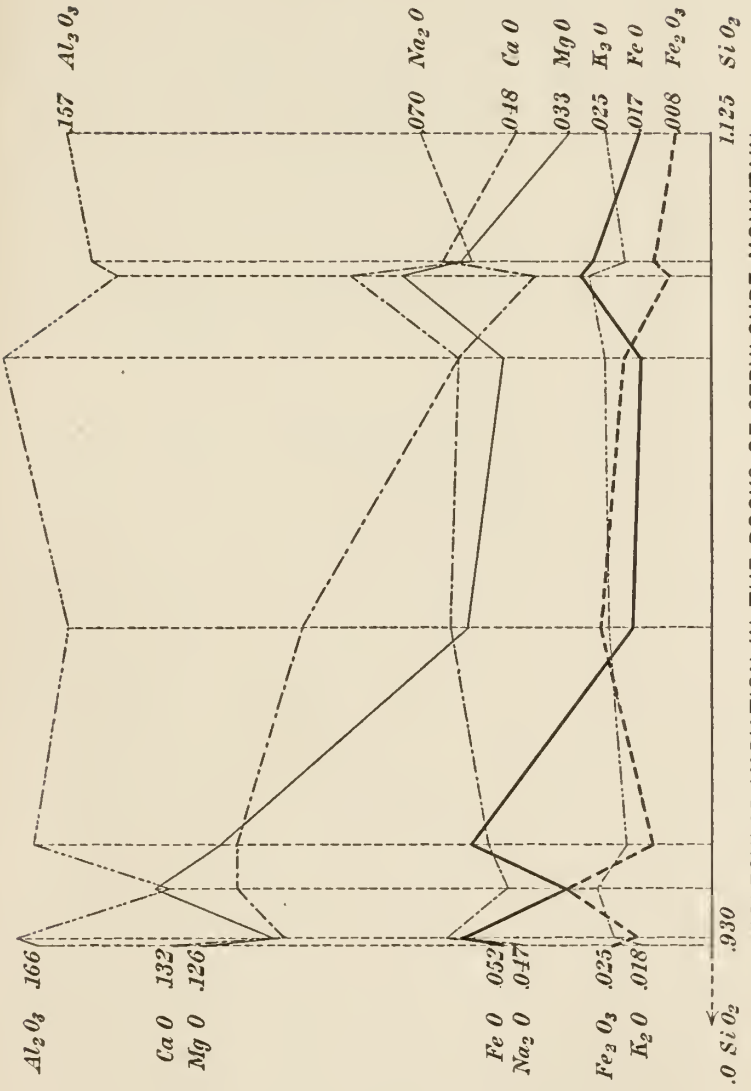
An examination of this diagram shows the same relations between the oxides as those observed for the group

TABLE IX.

Chemical Analyses of Volcanic Rocks from Sepulchre Mountain.

Specimen Number	219	694	214	221	217	2736	394	3017	3680
SiO_2	55.83	55.92	56.61	57.17	60.30	64.27	65.50	65.66	67.49
TiO_2	1.05	.94	.79	1.03	.76	.32	.45	1.37	.13
Al_2O_3	17.11	17.70	13.62	17.25	16.31	17.84	14.94	15.61	16.18
Fe_2O_3	4.07	3.16	5.89	2.48	4.35	3.36	1.72	2.10	1.30
FeO	3.75	4.48	2.60	4.31	1.41	1.29	2.27	2.07	1.22
MnO	none	tr.	.35	none	.13	none	.20	none	.08
CaO	7.40	5.90	6.61	6.61	5.62	3.42	2.33	3.64	2.68
BaO	. . .	. . .	.14	. . .	.15	. . .	.13	. . .	. . .
MgO	5.05	4.34	5.48	4.83	2.39	2.00	2.97	2.46	1.34
SrO	. . .	. . .	tr.	. . .	tr.	. . .	tr.?		
Li_2O	none	.09	. . .	tr.	. . .	.03	. . .	.36	
Na_2O	2.94	4.08	3.13	3.44	3.99	3.84	5.46	3.65	4.37
K_2O	1.71	2.28	2.71	2.03	2.36	2.48	2.76	2.03	2.40
P_2O_5	.21	.18	.06	.05	.20	.16	.09	tr.	.13
SO_3	tr.	tr.	?	tr.	.10	tr.	.06	.13	. . .
Cl	none	none	. . .	tr.	. . .	none	. . .	.12	
CO_2	. . .	. . .	none	. . .	none	. . .	none	. . .	. . .
H_2O	1.28	1.42	2.27	1.20	2.50	1.32	1.37	1.07	2.69
	100.40	100.45	100.26	100.40	100.57	100.33	100.25	100.27	100.01
Less O for Cl	. . .	. . .	. . .	. . .	. . .	. . .	. . .	.03	
								100.24	

TABLE X.


Al2 O3
157
Na2 O
070
Ca O
048
Mg O
033
K2 O
025
Fe O
017
Fe2 O3
008
Si O2
1.125
Al2 O3 166
Ca O .132
Mg O .126
Fe O .052
Na2 O .047
Fe2 O3 .025
K2 O .018
.0 Si O2 .930
MOLECULAR VARIATION IN THE ROCKS OF SEPULCHRE MOUNTAIN.

occurring at Electric Peak. They vary quite irregularly for a gradual change in the silica. The alumina varies rapidly and retains a high position. The alkalies gradually increase with the silica, the soda molecules being more than twice as numerous as those of potash. Magnesia experiences the greatest variation which is strikingly opposed to that of the alumina. The lime is less regular than in the Electric Peak group. The two oxides of iron are remarkably uniform in their reciprocal relations. The magnesia, lime and iron diminish with the increase of silica, while the alkalies increase, and the alumina decreases slightly. In this group of rocks also the oxidation of the iron bears a noticeable relation to the presence of hornblende and biotite and magnetite.

It is evident from a study of the analyses that the chemical variations in this group of volcanic rocks are the same in character and extent as those in the intrusive rocks of Electric Peak. Further, it is shown that the variations between similar varieties of andesite—such as those between different pyroxene-andesites—are as great, and in some cases greater than the variations between varieties of andesites which are distinguished mineralogically from one another. Thus 219 and 221 are pyroxene-andesites without hornblende; 214 and 217 are hornblende-pyroxene-andesites, while 694 is a hornblende-andesite. It is not possible to point to any chemical character of these rocks as distinctive of this mineral variation, with the exception of the oxidation of the iron, which, though slight, is an important one; for it undoubtedly relates to forces which did not alter the fundamental relation between the bases in the magma, but simply modified it by changing the oxidation of one of them

The last four analyses are of hornblende-mica-andesites and dacites. The chemical variations between them are quite as pronounced as those between the more basic members of the series, without there being the corresponding differences between the kinds of ferromagnesian silicates so far as it can be detected microscopically. They all carry horn-

blende and biotite and no pyroxene, the relative proportion of these minerals varying. The character and amount of the feldspars differ in these rocks, and so does the abundance and mode of occurrence of the quartz. In Nos. 3017 and 3680 quartz appears in porphyritical crystals; in the other rocks it is confined to the groundmass.

Comparing the two sets of analyses and the corresponding diagrams it is evident that the intrusive rocks of Electric Peak and the volcanic rocks of Sepulchre Mountain have the same chemical character. In fact, they are chemically identical, for the varieties that have been analyzed are but a few of the many mineralogical and structural modifications assumed by these series of rocks. The analyses serve as indications of the range of the chemical variability of the magma or magmas furnishing these rocks.

Furthermore the comparison demonstrates that the magmas that reached the surface of the earth in this place had exactly the same chemical composition as those which remained enclosed within the sedimentary strata. It proves with equal clearness that the different conditions attending the final consolidation of the extravasated and of the intruded magmas affected not only their *crystalline structure* but their *essential mineral composition.* The most marked illustration of this is in the occurrence of biotite in the two series. In the volcanic rocks of this locality biotite is an essential constituent of the more siliceous varieties, and is only rarely found as an accessory constituent of the varieties with less than 61 per cent. of silica. In the intrusive rocks it is an essential constituent of all the coarse grained varieties, even the most basic. In the finer grained porphyritic forms it is a constituent of the groundmass to a variable extent. The second most noticeable difference is the presence of considerable quartz in the coarse grained forms of the basic magmas, and its absence from the volcanic forms of the same magmas.

Correlation of the Rocks on a Chemical Basis.

Correlating the two groups of rocks according to their chemical composition as in Table XI, we see that the horn-

blende-mica-andesites, 2736, 394, are the equivalents of the quartz-mica-diorites, 3008, 2724, 2695, 2668, 2676. The dacites, 3017, 3680, are the equivalents of the quartz-mica-diorite-porphyrites, 3001, 2670. The hornblende-pyroxene-andesites and pyroxene-andesites, 219, 694, 214, 221, 217, are the equivalents of the coarse grained diorites, 2669, 2692, and of a fine grained facies, 2679, and they resemble certain porphyrites occurring in sheets, one of which is a hornblende-porphyrite, 2089, and the other a hornblende-mica-porphyrite, 154.

The dacites and hornblende-mica-andesites included within this correlation are intruded bodies within the breccia of Sepulchre Mountain, and have the same mineral composition as the corresponding porphyrites and diorites of Electric Peak. They differ from them in structure and degree of crystallization, the details of which cannot be described in this paper.

The glassy andesites with pyroxene and hornblende phenocrysts, however, present the utmost contrast to the equivalent coarsely crystalline diorites. In the former the hypersthene, augite, hornblende, and plagioclase are sharply defined, idiomorphic crystals of these minerals, scattered through a groundmass of glass, which is crowded with microlites of plagioclase and pyroxene besides grains of magnetite. The hornblende is brown, occasionally red, and the other phenocrysts have all the microscopical characters which distinguish their occurrence in glassy rocks. In the diorite the hornblende is green, in some cases brown; the hypersthene, augite, and hornblende are accompanied by biotite, and are all intergrown in the most intricate manner, with evidence that they commenced to crystallize in the order just given. The labradorite is often clouded with minute opaque particles, which are characteristic of its occurrence in many diorites; it is surrounded by a shell of more alkaline plagioclase, which, with occasional individuals of orthoclase and considerable quartz, closed the crystallization of the magma. Magnetite, apatite, and zircon

TABLE XI.

Correlation of the two Groups of Rocks upon a Chemical Basis.

		Volcanic Rocks of Sepulchre Mountain.		Intrusive Rocks of Electric Peak.	
SiO_2%	No.	Name.	Essential Minerals.	Name.	Essential Minerals.
			phenocrysts | *groundmass*		
69.24	2670	. . .	. . . . .	diorite-porphyrite . .	quartz, biotite, plagioclase, hornblende. | quartz and alkali fieldspar.
67.54	2676	. . .	. . . . .	quartz-mica-diorite . .	biotite, hornblende, plagioclase (orthoclase), quartz.
67.49	3680	dacite . .	quartz, biotite, hornblende, plagioclase. | holocrystalline, quartz and feldspar.		
66.05	2668	. . . .	. . . . .	quartz-mica-diorite .	biotite, hornblende, plagioclase (orthoclase), quartz.
65.97	3001	. . . . .	. . . . .	diorite-porphyrite . .	biotite, hornblende, plagioclase (orthoclase), quartz.
65.66	3017	dacite . . .	quartz, biotite, hornblende, plagioclase. | holocrystalline, quartz, feldspar.		
65.60	2695	. . . . .	. . . . .	quartz-mica-diorite	biotite, hornblende (pyroxene), plagioclase (orthoclase), quartz.
65.50	394	hornblende-mica-andesite .	hornblende, biotite, plagioclase. | holocrystalline, quartz, feldspar.		
65.11	2724	. . . . .	. . . . .	quartz-mica-diorite . .	biotite, hornblende, augite, hypersthene, plagioclase (orthoclase), quartz.
64.85	3008	. . . . .	. . . . .	quartz-mica-diorite . .	hornblende, biotite, plagioclase (orthoclase), quartz.
64.27	2736	hornblende-mica-andesite .	hornblende, biotite, plagioclase, magnetite. | holocrystalline, quartz, feldspar.		
61.50	154	. . . . .	. . . . .	hornblende-mica-porphyrite	biotite, hornblende, plagioclase, magnetite. | feldspar and quartz.
60.30	217	hornblende-pyroxene-andesite	hornblende, augite, hypersthene, plagioclase, magnetite. | glassy, microlitic.		
58.49	2089	. . . . .	. . . . .	hornblende-porphyrite .	hornblende, plagioclase, magnetite. | feldspar and quartz
58.05	2692	. . . . .	. . . . .	diorite	biotite, hornblende, augite, hypersthene, magnetite, plagioclase, (quartz).
57 38	2679	. . . . .	. . . . .	pyroxene-porphyrite . .	augite, hypersthene, biotite, magnetite, plagioclase, quartz.
57.17	221	pyroxene-andesite . .	augite, hypersthene, plagioclase. | brown glass, microlitic.		
56.61	214	hornblende-pyroxene-andesite	hornblende-augite-hypersthene, plagioclase. | glassy, microlitic.		
56.28	2669	. . . . .	. . . . .	diorite . . .	biotite, hornblende, augite, hypersthene, magnetite, plagioclase, quartz.
55 92	694	hornblende-andesite . .	hornblende, plagioclase. | microcrystalline.		
55.83	219	pyroxene-andesite . .	augite, hypersthene, plagioclase. | glassy, microlitic.		

are the accessory minerals. The quartz contains fluid inclusions, which complete the correspondence of this diorite with typical diorites of other regions.

Conclusions.

When we consider the geological structure of the region; the occurrence at Electric Peak of a broad body of eruptive rocks that have broken up successively through the same general channel, and that have imparted sufficient heat to the surrounding Cretaceous strata to highly metamorphose them for a considerable distance; the existence of a system of fissures filled with dikes of porphyrite that radiate outward toward the south and southwest; and when we observe at Sepulchre Mountain that an accumulation of breccia, resting on the Cretaceous, is traversed by a system of dikes radiating outward toward the north and northeast; the two systems being separated and probably disconnected by a profound fault—

When we further consider the petrographical resemblance between the dike rocks of the two places, the correspondence of habit between the more acid members of both series, and the chemical identity of the magmas involved, we feel justified in concluding that:

I. The volcanic rocks of Sepulchre Mountain, and the intrusive rocks of Electric Peak were originally continuous geological bodies.

II. The former were forced through the conduit at Electric Peak during a series of more or less interrupted eruptions.

III. The great amount of heat imparted to the surrounding rocks was due to the frequent passage of molten lava through this conduit.

IV. Portions of the different magmas erupted found their way into vertical fissures and took the form of dikes; portions reached the surface and became lava-flows and breccias, while portions remained in the conduit.

V. The various portions of the magmas solidified under a variety of physical conditions, imposed by the different geological environment of each, the most strongly contrasted of which were the rapid cooling of the surface flows under very slight pressure, and the extremely slow cooling of the magmas remaining within the conduit under somewhat greater pressure.

It is to be remarked that the first of a series of eruptions would pass through a colder conduit than the last magmas would, consequently the rate of cooling would be different in each case, and the pressures at which crystallization sets in would also differ. This difference would also obtain between the advance and rear ends of the magma of a single eruption, and should be more marked in the first eruptions of a series than in the last, since the temperature of the conduit increases during the period of eruptions. Hence the first part of a magma may carry porphyritical crystals while the latter portion may be free from them.

VI. We have in this region the remnant of a volcano, which has been fractured across its conduit, has been faulted and considerably eroded; and which presents for investigation, on the one hand, the lower portion of its accumulated débris of lavas, with a part of the upper end of the conduit filled with the final intrusions; and on the other hand a section of the conduit within the sedimentary strata upon which the volcano has been built.

We find that the lower portion of the basic breccia is made up of andesites carrying phenocrysts of augite, hypersthene and plagioclase, and of other basic andesites without macroscopic crystals. The former correspond to a facies of the diorite in the conduit carrying the same kinds of phenocrysts; while the second modification of the andesite corresponds to the greater part of the basic diorite. For it is evident

UPB

from a study of this diorite that much of its magma reached its position in the conduit in a completely fused condition, after which it crystallized into hypersthene, augite, hornblende, biotite, labradorite, alkali feldspars and quartz, with accessory magnetite, apatite and zircon. We feel justified, then, in the further conclusions:

VII. That the molecules in a chemically homogeneous, fluid magma combine in various ways, and form quite different associations of silicate minerals, producing mineralogically different rocks.

VIII. In this region the greatest mineralogical differences accompany the greatest differences in structure or degree of crystallization; hence, the causes leading to each are coëxistent.

IX. The causes of these mineralogical and structural differences must be sought in the differences of geological environment, and these affect the rate at which the heat escapes from the magmas, and the pressure they experience during crystallization.

Since it has been demonstrated by synthetical research that water- and other vapors are potent factors in the crystallization of quartz and other minerals that have not been produced artifically without their aid, and as there is ample evidence both in the extravasated lavas and in the coarsely crystallized rocks in the conduit that water-vapor was uniformly and generally distributed through the whole series of molten magmas, and no evidence that there existed in the magmas which stopped within the conduit any more or different vapors than those which existed in the magmas that reached the surface, we may conclude that—

X. The *efficacy* of these absorbed vapors as mineralizing agents has been *increased* by the conditions attending the solidification of the magmas within the conduit.

For, if it is necessary, as advocated by the French geologists, MM. Michel Lévy,* de Lapparent† and others, to refer the crystallization of certain minerals, as quartz, to the mineralizing influence of absorbed vapors, it is evident that the required mineralizing agent is universally present in sufficient quantities, since there are no instances where a magma of the requisite chemical composition has failed to crystallize completely with the development of quartz when subjected to the proper physical conditions.

However, it is probable that differences in the amount or in the kind of mineralizing agents produce differences in the degree or nature of the crystallization of similar magmas which have solidified with the same geological environment.

It has been suggested by Mr. H. J. Johnston-Lavis‡ that the nature of the rocks surrounding a conduit, through which molten magmas pass, materially affects the amount and character of the vapors introduced into these magmas, which will vary as the surrounding rocks are more or less porous and are saturated with different kinds of waters. The effect of these vapors on the structure and composition of igneous rocks is also discussed by the same writer.

The effect of differences in the amount of the mineralizer in a single magma is well illustrated in the structure of the obsidian at Obsidian Cliff, Yellowstone National Park, § where the alternating layers of holocrystalline and glassy rock appear to be unquestionably due to the irregular distribution through the magma of vapors, which in the upper portion of the flow have produced alternating layers of pumice and compact glass. The mineralizing agent was present, however, in the alternate glassy layers as well as in the crystallized or in the pumiceous ones, for in the highest

*"Structures et Classification des Roches Éruptives." Paris, 1889. pp. 5 and 12.

†Revue des questions Scientifiques. Paris, 1888. 36.

‡"The Relationship of the Structure of Rocks to the Conditions of their Formation." Sci. Proc. of the Royal Dublin Soc. Vol. V (n. s.), part 3, July, 1886, pp. 113 to 155.

§Obsidian Cliff, Yellowstone National Park, by J. P. Iddings. Seventh Annual Report of the Director of the U. S. Geological Survey, Washington, 1888, p. 287.

portion of the flow the whole mass is pumiceous but in different degrees, and the presence of absorbed vapors may be detected chemically and physically in the compact layers. Its amount, however, was not sufficient to produce complete crystallization under the attendant physical conditions. Its effectiveness in this case was controlled by the geological occurrence of the magma.

It is to be observed, in addition, that, whatever the mineralizing vapors in acid magmas may be, there is the same evidence of their existence in intermediate and in basic magmas, whether we investigate them chemically or physically, or study the phenomena of their geological occurrence. There are even indications of their greater abundance in the basic lavas, many of whose glasses contain a high percentage of water, and the highly vesicular character of whose lava-flows is universal. Nor are the geological evidences less conclusive that demonstrate the existence of abundant explosive agents in the basaltic and andesitic magmas that have hurled their shattered masses over broad areas of country, and have piled vast accumulations of basaltic breccia throughout our western territory.

Nevertheless, with all these evidences of the universal presence of mineralizing agents in basic magmas, we do not recognize their influence upon the microstructure or crystallization of basic lavas. We may assume, then, that in the majority of these cases they have no influence.

But when the basic magmas become coarsely crystalline, and separate into minerals, the crystallization of some of which we have already referred to the action of mineralizing vapors, we may logically assume that in these cases the absorbed vapors have influenced the crystallization of the magmas.

If this reasoning is correct, then the action of mineralizers upon basic magmas is controlled by the physical conditions under which they solidify.

Finally, if mineralizing agents are universally present in igneous magmas, and if their action, so far as we can ob-

serve it, is controlled by the physical conditions imposed by the geological history of each eruption, we should not regard the presence or absence of certain minerals, relegated to the influence of mineralizing agents, as evidence of the presence or absence of these agents in the molten magma; but we should see in it the evidence of special conditions controlling the solidification of the magma, and should seek the fundamental causes of the mineralogical and structural variations of a rock in the geological history of its particular eruption.